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Estimating population size of a nocturnal burrow-nesting seabird using acoustic monitoring and habitat mapping

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Abstract

Population size assessments for nocturnal burrow-nesting seabirds are logistically challenging because these species are active in colonies only during darkness and often nest on remote islands where manual inspections of breeding burrows are not feasible. Many seabird species are highly vocal, and recent technological innovations now make it possible to record and quantify vocal activity in seabird colonies. Here we test the hypothesis that remotely recorded vocal activity in Cory's shearwater (*Calonectris borealis*) breeding colonies in the North Atlantic increases with nest density, and combined this relationship with cliff habitat mapping to estimate the population size of Cory's shearwaters on the island of Corvo (Azores). We deployed acoustic recording devices in 9 Cory's shearwater colonies of known size to establish a relationship between vocal activity and local nest density (slope = 1.07, R^2 = 0.86, $p < 0.001$). We used this relationship to predict the nest density in various cliff habitat types and produced a habitat map of breeding cliffs to extrapolate nest density around the island of Corvo. The mean predicted nest density on Corvo ranged from 6.6 (2.1–16.2) to 27.8 (19.5–36.4) nests/ha. Extrapolation of habitat-specific nest densities across the cliff area of Corvo resulted in an estimate of 6326 Cory's shearwater nests (95% confidence interval: 3735–10,524). This population size estimate is similar to previous assessments, but is too imprecise to detect moderate changes in population size over time. While estimating absolute population size from acoustic recordings may not be sufficiently precise, the strong positive relationship that we found between local nest density and recorded calling rate indicates that passive acoustic monitoring may be useful to document relative changes in seabird populations over time.

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Keywords
Cory's shearwater, *Calonectris borealis*, vocal activity, nest density, Random Forest, Azores, Macaronesia, Procellariformes

Introduction

Seabirds are globally the most threatened group of birds (Croxall et al. 2012), and assessing the severity of threats or the effectiveness of conservation measures requires periodic assessments of population size to understand whether populations are declining or increasing. Estimating population trends remains challenging for many seabird species due to logistical constraints imposed by often inaccessible breeding locations on remote islands. In addition, several seabird species nest in burrows or cavities, and are active in breeding colonies only during the hours of darkness. For these nocturnal burrow-nesting seabirds visual assessments of population size are not possible, and robust estimates of population size are usually based on marking a large number of birds (Sanz-Aguilar et al. 2010; Sutherland and Dann 2012) or estimates of burrow occupancy (Pearson et al. 2013). On many islands the marking of seabirds or inspection of burrows is logistically not feasible, because birds nest on inaccessible cliffs. As a consequence of the various logistical constraints, the population sizes of many species of storm-petrels, petrels, shearwaters and alcids are very poorly known (Brooke 2004; Croxall et al. 2012). The burrow-nesting habit of many species, which directly influences the complexity of population assessments, also contributes to their vulnerability to invasive alien predators, a key threat to seabirds (Croxall et al. 2012; Jones et al. 2008). Thus, the group of species for which assessments of population size are critical is also one of the most difficult to monitor.

Monitoring the population size of nocturnal burrow-nesting seabirds has recently benefited from autonomous acoustic recording devices, which can be deployed on remote islands to record the vocal activity of seabirds (Buxton and Jones 2012; Buxton et al. 2013; McKown et al. 2012; Borker et al. in press). Acoustic recording is a promising approach for many biodiversity assessments (Celis-Murillo et al. 2012; Penone et al. 2013; Sueur et al. 2008; Wimmer et al. 2013), and has been successfully employed to assess the changes in seabird breeding populations following island restoration (Buxton et al. 2013). The number of recorded seabird vocalisations is expected to increase in larger colonies, but to our knowledge no attempt has been made to estimate absolute population size of a nocturnal burrow-nesting seabird species based on vocal activity rates measured from acoustic recordings.

Here we present a case study for estimating the population size of Cory's shearwater (*Calonectris borealis,* recently split from *C. diomedea* (Sangster et al. 2012)) nesting on a rugged island in the Azores archipelago in the North Atlantic Ocean. The Azores are estimated to hold a significant proportion of the Cory's shearwater world population, with a breeding population between 49.500 and 89.000 pairs (Monteiro et al. 1996).

All populations are affected by introduced predators (Fontaine et al. 2011; Hervías et al. 2013), but for most islands it is unknown whether populations are declining or stable because no quantitative estimates of population size exist. Robust population size estimates are a key knowledge gap for the protection of seabirds in the Azores (Ramírez et al. 2008). To address this knowledge gap, we deployed acoustic recording devices in Cory's shearwater colonies of known size to calibrate the relationship between vocal activity and local nest density. We used this relationship to predict the nest density at other recording stations where a count of occupied nesting burrows was not possible. We further produced a habitat map of breeding cliffs and extrapolated nest density around the island of Corvo based on the habitat composition of breeding cliffs. This approach yielded the first quantitative estimate of the breeding population of an island that is believed to hold one of the largest Cory's shearwater populations in the world (Furness et al. 2000; Granadeiro et al. 2006; Monteiro et al. 1996).

Methods

Study area

Corvo is a small (1700 ha) island of volcanic origin located in the central North Atlantic (39°40'N, 31°7'W). The volcanic cone of the island rises to 718m, and due to wind and wave action much of the volcanic cone has eroded, particularly on the western coast. The erosion has led to almost vertical cliffs between 200–600 m tall along the majority (16.3 km) of Corvo's coastline. Due to the inaccessible nature of the cliffs, the size of the Cory's shearwater population has never been quantified (Furness et al. 2000), but based on counts of birds rafting offshore it has been estimated that 6000–12,000 pairs or 30.000 individuals nest on the island (Monteiro et al. 1996; Ramírez et al. 2008).

Acoustic recording and nest density assessment

In May 2011 and 2012, we deployed a total of nine autonomous acoustic recorders (SongMeter SM2, Wildlife Acoustics Inc., Concord, MA) in colonies that were expected to have varying nest density of Cory's shearwaters, but where all burrows and potential nest cavities within a 50 m radius could be manually inspected to assess local nest density. These colonies were situated on Corvo as well as on the islands of Faial (38°35'N, 28°48'W), and Vila Franca do Campo (37°42'N, 25°26'W) in habitats similar to the cliffs on Corvo. In May 2012, we deployed 12 additional acoustic recorders in various cliff habitats on Corvo where nest density assessment was not possible, including near-vertical cliffs where recorders were deployed with ropes. All recorders were deployed in wind-sheltered areas on the ground or a cliff ledge, with two independent microphones elevated 30 cm above ground and spaced < 50 cm apart.

Recorders operated on an identical schedule for the entire breeding season (late May to mid October), with 1 min recordings every 10 min from local sunset to local sunrise. Gain on both independent microphones was set to the default of +42.0 dB and sound was recorded at a sample rate of 16 kHz in stereo.

In June 2011 and 2012, we searched for occupied shearwater burrows within a 50 m radius of the nine accessible recorders, based on the assumption that SongMeters can record vocalisations up to 50 m away (Buxton and Jones 2012). All potential burrows and rock cavities were inspected with a burrow-scope, and those containing an adult bird or an egg were considered as occupied and monitored for a different project (Hervías et al. 2013). The nest density around the nine accessible acoustic recorders was therefore known.

Acoustic data processing and calibration

Vocal activity of burrow-nesting seabirds at colonies is dependent on many environmental factors and thus varies considerably within nights and over the breeding season (Bretagnolle et al. 2000; Granadeiro et al. 2009). Instantaneous vocal activity is therefore unlikely to accurately predict nest density, which has affected acoustic population assessments made by human observers in the past (Bolton et al. 2010). To reduce variation in vocal activity and increase correlation between vocal activity and nest density we first excluded data from time periods when calling rates were expected to be lower and more variable, and averaged the calling rate over the remainder of the breeding season as a single metric of vocal activity per recorder location. Specifically, we discarded recordings from September onwards when thermally independent chicks require less attention by their parents and attendance and vocal activity at the colony decreases (Granadeiro et al. 1998; Magalhães et al. 2008; Paiva et al. 2010). Further, we limited recordings to 22:00–01:00 hrs local time and moon phases where < 75% of the moon was illuminated to capture the periods when vocal activity around the colony was most consistent (Granadeiro et al. 1998; Hamer and Read 1987; Mougeot and Bretagnolle 2000). Nonetheless, the attendance cycles of Cory's Shearwaters at colonies are cyclic and not all of the variation in attendance and vocal activity can be explained by the factors described above (Mougin et al. 2000). The main advantage of autonomous acoustic recorders to overcome such unexplained variation is their ability to record vocal activity consistently over long time periods and thus average out short-term variation in attendance or vocal activity patterns (Buxton and Jones 2012). After having excluded the data with lower or more variable vocal activity described above, we used the mean number of Cory's shearwater vocalisations in all remaining 1 min recordings from late May until the end of August as metric of vocal activity around each recorder.

Due to the long deployment period, the recorded vocal activity could not be assessed manually but required an automated call recognition algorithm (Brandes 2008; Digby et al. 2013; Rempel et al. 2013; Swiston and Mennill 2009). We performed automated analyses of all field recordings with the eXtensible BioAcoustic Tool (XBAT,

http://www.xbat.org), a bioacoustic analysis software package for MATLAB that includes algorithms for detecting sounds of interest in acoustic recordings. Specifically, we used an image processing technique known as spectrogram cross-correlation to detect and classify sounds in our field recordings that were correlated with the spectral characteristics of typical Cory's shearwater vocalizations (Mellinger and Clark 2000). To assess the effectiveness of this detection algorithm we created a control dataset from field recordings obtained in June and July 2011 in which we manually marked all shearwater calls. We then measured the performance of the detection algorithm by comparing the detected calls to the known calls in the control dataset. The detection algorithm was accurate in that > 88% of the calls detected were actual shearwater calls. In addition, the template detected 57% of the total number of manually identified calls in the control dataset. We applied this detection algorithm to all acoustic recordings, and manually audited all positive recognitions to remove erroneous classifications of background noise as Cory's shearwater vocalisations. This process resulted in a minimum number of Cory's shearwater vocalisations for each 1-min recording file.

To calibrate the relationship between local nest density and vocal activity, we used the nine accessible recorders where local nest density was known. Because we expected vocalisations to increase linearly with nest density, we fitted a linear regression to the mean number of shearwater calls per minute with nest density as dependent variable. This linear relationship was then used to predict local nest density at the remaining 12 recorders that were placed in locations where nest burrows could not be manually surveyed.

Cliff habitat mapping

To be able to extrapolate local nest density assessed via acoustic recorders to the entire suitable nesting area for Cory's shearwaters on Corvo, we adopted a habitat modelling approach to predict nest density in different cliff micro-habitats following similar work in mountainous areas (Oppel et al. 2004). We took digital pictures of the cliffs from a boat while circumnavigating the island to create a habitat map of the near vertical cliff habitat. Pictures were taken at 90 sampling points spaced 140-180 m apart and 300 m from the shoreline to ensure wide overlap in the field of view between adjacent sampling points. The pictures were then merged into composite images of the cliffs surrounding the island with the software GIMP 2.7 (Immler 2010).

The composite cliff panoramas were visually inspected and homogenous areas of similar habitat type were manually delineated as polygon features in a geographic information system (ArcMap 10.1, ESRI Inc., Redlands, CA). Each delineated polygon was given a value for three habitat features (Immler 2010). Habitat features were selected for the unique cliff environment of Corvo and the burrow-nesting habits of Cory's shearwaters (Furness et al. 2000; Ramos et al. 1997). We classified habitats based on inclination (< 60°; 60–85°, and > 85°), rock type (flat without ledges, cracks, or crevasses; broken rock with ledges, furrows, cavities; no rock), and soil layer (very shallow layer of soil unsuitable for burrow excavation; deep enough for burrow excavation).

The same three habitat features were also recorded around the location of each acoustic recording device. This allowed us to use the estimated nest density inferred from the recorded calling rate in a habitat model to predict the nest density in relation to the three habitat features, and thus assess density in those combinations of habitat features where no recorder had been placed.

Extrapolation of breeding population size

We first estimated the local nest density for all recording units based on the acoustic calibration relationship described above. We then related the estimated nest density at each recorder to the three habitat features to establish a predictive relationship between the level of each habitat feature and nest density (Pearson et al. 2013). Because we had only a small dataset to train this model (n = 21 recorder locations with estimated nest density), we used a powerful machine-learning algorithm based on ensembles of regression trees (Random Forest) to predict nest density for each combination of habitat features that existed along the coast of Corvo (Cutler et al. 2007; Hochachka et al. 2007; Olden et al. 2008). We used the R package 'randomForest'to construct 2500 regression trees, and used this model to predict nest density in all habitat types along the cliff. This habitat-specific nest density prediction required prediction to new combinations of the three habitat features, as only 9 of the total of 17 different combinations of the habitat features were present in the recorder data used to construct the Random Forest model. However, each level of our habitat features was represented at 3–14 recorder locations, and our predictions therefore did not extrapolate into unknown sampling space, but merely interpolated into the inferred sampling space where predictions are generally more reliable (Zurell et al. 2012). To assess whether the habitat model reliably predicted nest density we performed a cross-validation. This cross-validation tested whether a model constructed without a given recorder would adequately predict the nest density based on the habitat data at that recorder location. We then correlated the predicted nest density from the habitat model with the nest density at that recorder and concluded that our model was able to predict nest density at habitat types that were not present in our training data if there was a significant positive correlation.

To extrapolate from nest density to total population size of Cory's shearwaters, we used the habitat feature map derived from digital photographs to calculate the proportion of the entire cliff area that was covered by polygons with each combination of habitat features. The proportion of each habitat type was multiplied by the entire area of suitable cliff habitat around Corvo, estimated from the length of the coastline (16.3 km) and the height of cliffs to be 490 ha.

We then summed the number of shearwater nests predicted to occur in each habitat across the entire island to derive an estimate of island-wide breeding population size of Cory's shearwaters. We present the estimate of breeding population size with 95% confidence intervals derived from the linear regression predicting nest density around each recorder.

Results

The mean calling rate per 1-min recording ranged from 0.7 to 55.2 Cory's shearwater calls at the nine recorders with known local nest density, and from 0–25.1 calls at the recorders placed at inaccessible cliff locations. We counted between 8–56 occupied Cory's shearwater burrows in a 50 m radius around accessible recorders, and found a relationship that indicated a linear increase in local nest density with increasing calling rate (slope = 1.07, R^2 = 0.86, $p < 0.001$; Fig. 1). Based on this relationship, the mean predicted nest density around the 12 recorders where no nest count had been feasible was 9.5 nests/ha (95% confidence interval 4.1–18.5 nests/ha).

The 21 acoustic recorders were placed in nine different combinations of the three habitat variables and represented all levels of the three habitat features. The Random Forest habitat model relating estimated nest density to habitat features performed well in cross-validation and observed and predicted nest densities were positively correlated (Pearson r = 0.73, $p < 0.001$). This model predicted that nest density across all combinations of habitat features on Corvo ranged from 6.6 (2.1–16.2) to 27.8 (19.5–36.4) nests/ha (Table 1).

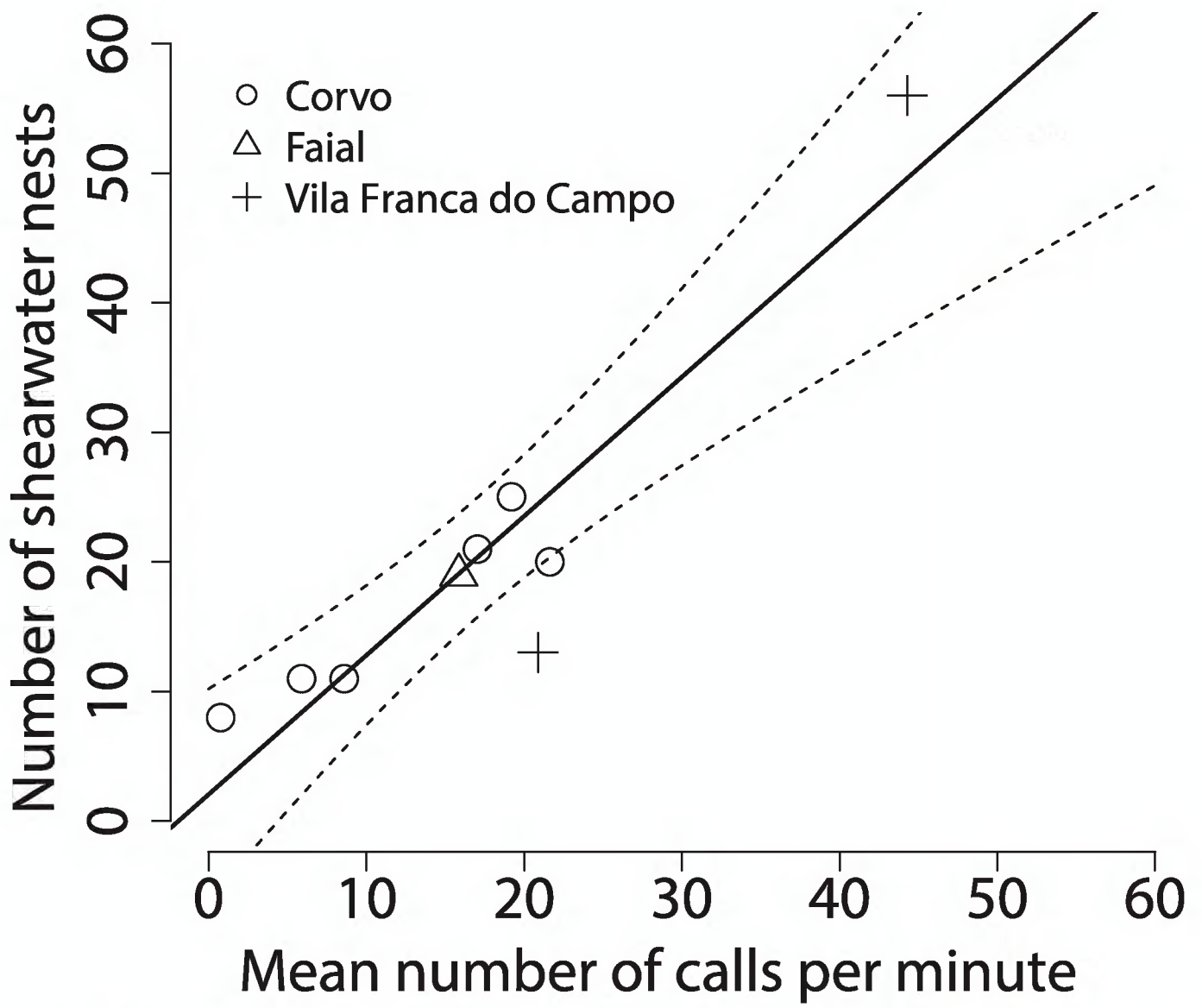

Figure 1. The number of occupied Cory's shearwater nests within a 50 m radius around acoustic recording devices increased with mean shearwater call rates measured during the 2011 and 2012 Cory's shearwater breeding seasons (solid line = linear regression with slope = 1.07, R^2 = 0.86, $p < 0.001$; broken line = 95% confidence intervals). Different symbols represent data from three islands in the Azores, North Atlantic Ocean.

Table 1. The distribution of estimated nest densities and number of estimated Cory's shearwater nests (with 95% confidence intervals) around the 490 ha of cliff habitat on the island of Corvo (Azores) in 2012.

Soil Type	Rock type	Inclination	Area (ha)	Nest density (nests/ha)	N nests
deep	flat rock	<60°	2.2	27.8 (19.5–36.4)	62 (43–81)
deep	flat rock	>85°	3.8	23.5 (15.9–31.9)	89 (60–120)
deep	broken rock	<60°	45.1	23.3 (17.2–30.3)	1050 (776–1367)
shallow	flat rock	>85°	3.9	23.1 (15.9–31.2)	90 (62–121)
shallow	flat rock	<60°	1.8	22.1 (14.8–31)	40 (27–56)
deep	flat rock	60-85°	2.3	17.1 (10.4–26.6)	40 (24–62)
deep	broken rock	>85°	82.4	16.7 (11.2–24.4)	1378 (923–2012)
deep	no rock	<60°	3.3	16.3 (9.2–24.7)	54 (30–81)
shallow	flat rock	60-85°	0.2	15.5 (9.4–24.9)	4 (2–6)
shallow	broken rock	>85°	5.3	13.8 (8–22)	72 (42–116)
shallow	broken rock	<60°	71.2	13.4 (7.9–22)	955 (565–1565)
deep	no rock	>85°	1.7	12.5 (6.3–20.9)	22 (11–37)
shallow	no rock	<60°	89.8	11.1 (5.2–20.1)	1001 (466–1808)
deep	broken rock	60–85°	92.5	10.3 (5.8–19.3)	949 (541–1785)
deep	no rock	60–85°	2.6	8.2 (3–17.4)	21 (8–45)
shallow	no rock	60–85°	35.8	6.7 (1.9–16.2)	241 (68–581)
shallow	broken rock	60–85°	42.6	6.6 (2.1–16.2)	283 (88–691)

Highest nest densities were predicted either on vertical cliffs (> 85° inclination) with flat rock, or in less steep areas (< 60°) with deep soil suitable for excavating burrows. Lowest nest densities were predicted in areas with intermediate inclination (60-85°) and no flat rock (Table 1). Extrapolating the estimated habitat-specific densities across the entire cliff area of Corvo resulted in an estimate of 6326 Cory's shearwater nests (95% confidence interval: 3735–10,524).

Discussion

Based on acoustic recording and habitat mapping we estimated that >6000 pairs of Cory's shearwaters nested on Corvo in 2012. This population size estimate is surrounded by considerable uncertainty (3735–10,524 pairs), which describes the potential range of the Cory's shearwater population on Corvo. Due to this large uncertainty our estimate is unlikely to serve as a useful baseline for assessing moderate changes in population size.

Our population size estimate is of a similar magnitude as previous extrapolations for Corvo (6000–12,000 pairs in 1996), which were derived from counting individuals rafting at sea or multiplying average breeding densities by the area of available habitat (Monteiro et al. 1996; Ramírez et al. 2008). Up to 15,000 individual Cory's shearwaters can be regularly observed rafting close to Corvo during the breeding season, but raft counts of shearwaters typically include a large number of non-breeding

birds (Feio and Monteiro 1998). Nonetheless, these raft observations indicate that the order of magnitude of our population estimate is realistic. The nest densities recorded or estimated in this study were at the lower margin of the densities presented by Monteiro et al. (1996; 20–60 nests/ha) and much lower than nest densities recorded for Cory's shearwaters along the cliffs of Selvagem Grande (283 ± 57 nests/ha), the largest Cory's shearwater colony in the world (Granadeiro et al. 2006). The Cory's shearwater population on Corvo thus appears to be smaller and nest at a lower density than the breeding populations in the Selvagem archipelago, despite being the largest colony in the Azores (Furness et al. 2000). It is possible that the Cory's shearwater population on Corvo may have been much larger in the past (Bolton 2001; Monteiro et al. 1996), as introduced cats (*Felis catus*) and rats (*Rattus rattus*) continue to affect breeding success of seabirds on many islands in the Azores (Fontaine et al. 2011; Hervías et al. 2013).

The large uncertainty in our abundance estimates is a consequence of error propagation across two different model predictions – the predicted nest density based on recorded calling rate, and the predicted overall abundance extrapolated from the predicted nest density per habitat type. Additional uncertainty may arise because nest density may vary due to social attraction and the presence of invasive predators in addition to suitable habitat (Igual et al. 2007; Major and Jones 2011). While more intensive calibration work with more recorder locations across an exhaustive habitat gradient and more precise habitat mapping might lead to tighter relationships between recorded calling rate and nest density, and between predicted nest density and habitat features, such intensive work is likely not realistic for the majority of remote islands for which population assessments of nocturnal burrow-nesting seabirds are required.

Despite the imprecise population size estimate, our work suggests that there is a positive relationship between calling rate recorded by autonomous acoustic recorders and seabird nest density. This finding builds on previous work (Brandes 2008; Buxton and Jones 2012; Buxton et al. 2013; Borker et al. in press) and suggests that acoustic recording may offer a practically feasible approach to monitor relative population changes of nocturnal burrow-nesting seabirds on remote islands. Continuous developments in hardware and data management (McKown et al. 2012) as well as automated call recognition algorithms (Digby et al. 2013) will make acoustic monitoring a useful tool for many remote seabird breeding colonies. Based on our work we are doubtful that the absolute size of seabird populations can be estimated with sufficient precision and accuracy based on acoustic recordings alone. Nonetheless, because the recorded calling rate of shearwaters increased with local nest density in our study, we believe that vocal activity recorded with autonomous acoustic recorders can be used as an adequate index of population size for long-term monitoring or assessing the effects of island restoration (Buxton et al. 2013). Such an approach relies on fewer assumptions than our extrapolations of population size, and may therefore be more reliable for long-term monitoring. However, using the recorded calling rates as an index of colony size would still rely on some critical assumptions, particularly that the number of non-breeding individuals present at the colony is similar between years

and that the calling rate increases in a linear or otherwise predictable fashion with nest density. Although not evident in our dataset, acoustic recordings in very large and dense seabird colonies may overload any call detection algorithm if too many calls are recorded simultaneously. Thus, there may be an upper limit of vocal activity beyond which any further increase in colony size can no longer be detected with currently available acoustic devices and data processing algorithms. We encourage researchers working at accessible seabird colonies to employ acoustic monitoring simultaneously to traditional monitoring approaches to establish whether temporal trends in population size can be detected using acoustic monitoring.

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